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DRAG REDUCTION FROM FORMATION FLIGHT

Flying Aircraft In Bird-Like Formations Could Significantly Increase Range

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TITLE: Drag Reduction from Formation Flight

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The Air Vehicles Directorate is currently studying a novel form of formation flight. For centuries, flocks of migratory birds have flown in large formations. One reason for this is the drag reduction that is obtained by flying in close proximity to wakes generated by other birds. Photographic studies of Canadian Geese indicate the average spacing between adjacent birds is very close to the optimum predicted by simple aerodynamic theory. Small heart monitors implanted in White Pelicans show reduced heart rates while flying in formation compared to individual flight. Recent advances in automatic control theory combined with the ability to accurately determine the location of aircraft may now make this practical for aircraft.

Aircraft wings generate strong tip vortices (like horizontal tornadoes) that generate large downward velocities ("downwash") between the wing tips and upward velocities ("upwash") outboard of the tips. For some aircraft, the velocities at the edge of these vortices can exceed 100 miles per hour. By properly positioning the wing of another aircraft within this upwash, the effective velocity vector of the aircraft is rotated downward. This rotates the lift vector forward and the drag vector upward, giving the impression of flying downhill. The net effect is a decrease in drag as measured with respect to the flight path. The phenomenon is *not* "drafting", which bicycle and automobile racers use to reduce wind resistance.

The upper limit on the theoretical benefit in range increases with the square root of the number of aircraft in the formation. For example, the range of nine aircraft in formation would by three times the range of a single aircraft. Introducing only a single constraint, that the formation cruises at the same altitude that single aircraft currently use, reduces the benefit for a nine aircraft formation to an 80% increase. Other considerations like engine performance and atmospheric turbulence reduce the value even further. The increase that is actually attainable is being studied in wind tunnel and flight tests.

One of the difficulties in maintaining minimum drag formations is that trailing aircraft within the formation are not in a stable position and will have a tendency to wander. To maximize the drag reduction, the aircraft must fly within the same horizontal plane (coplanar). Although flight demonstration teams like the USAF Thunderbirds or Navy Blue Angels fly very close to one another, they generally fly in stable positions with respect to each other. The appearance that the vehicles are coplanar is an optical illusion. The wing aircraft in the famous "diamond" formation actually fly above the lead aircraft while the trail aircraft flies either above or below the leader. If the flight path is nearly perpendicular to the line of sight, these vertical separations cannot be discerned and it appears that the vehicles are coplanar. Another difficulty with minimum drag formations is large control deflections may be necessary to maintain position. The beneficial upwash is predominant on the wing nearest to the formation leader, resulting in a tendency to roll the trail aircraft away from the leader. The control required to counter this roll increases drag, reducing the overall benefit.

Bihrle Applied Research of Hampton Virginia, under an Air Vehicles Directorate Small Business Innovation Research Phase II program, recently modified the Langley Full Scale 30x60 ft wind tunnel to allow it to measure the forces acting on both aircraft while in a formation. Tests using two tailless delta wing UAV models showed peak drag reductions of about 15% for the trail aircraft in a two-ship formation. The maximum drag reductions occurred when the wingtips overlapped slightly. Large pitching and rolling moments were also measured which would require control deflections to counteract. Air Vehicles Directorate Scientists, using the vortex lattice code HASC95, computed a drag reduction of just over 20%, slightly more optimistic than the experimental results. HASC95 was also used to define stability boundaries for the trail UAV. The computed boundaries were very close to those measured in the Langley tests. Air Vehicles Directorate Scientists also developed advanced control algorithms for maintaining a UAV formation using neural networks. Flight simulations showed that the trail UAV was able to track the lead UAV during high speed flight and maintain proper position with only small deviations during banking maneuvers.

Wind tunnel tests were also conducted using two 1/10 scale F-18C models, which showed peak drag reductions of about 25%. These tests support the Autonomous Formation Flight program underway at the NASA Dryden Flight Research Center. NASA modified two F-18's with an updated control system designed to maintain proper formation position. The system uses differential GPS measurements to determine the relative location of the aircraft.

The Air Force Flight Test Center is also studying formation flight, using T-38's. In October 2001, two and three-ship formations of T-38's were flown in various positions while in echelon formation. Aerodynamic theory indicates that the third ship in a formation has a larger drag reduction than the second. Air Force Institute of Technology and Air Vehicles Directorate Scientists performed extensive pre-test calculations of the formation flight effects using the HASC95 code. The calculations were performed at the flight test condition (Mach=0.5) and included control surface deflections for aircraft trim. They indicated a 15% drag reduction for the trail ship in a two ship formation and a 18% reduction for the third ship in an echelon. These results are smaller than the tailless UAV results because the flight tests could not be conducted at the speed for optimum drag reduction. At the optimum speed, drag reductions of almost 30% were predicted. The flight tests did not directly measure drag but instead measured fuel flow, which is representative of the actual benefits in terms of dollars saved. Fuel flow savings were measured using two distinct methods. Direct measurements of fuel flow were made for the trail aircraft in formation and out of formation but at the same airspeed. An indirect measurement was made by comparing the airspeed difference of the trail aircraft in and out of formation at the same throttle setting. This speed difference was put into a high fidelity engine model and used to estimate the change in required fuel flow. Four lateral separations were tested, two with overlapped wingtips, one with wingtips aligned, and one with a gap between the wingtips. There was no overlap in the longitudinal direction, a twelve foot nose to tail separation was maintained between adjacent aircraft. The maximum fuel savings was found with the wingtips overlapped by 14% of their span, in agreement with the pre-test calculations. For the two-ship formation, an 11% fuel flow reduction was found using the direct method while the indirect method indicated a 7% reduction. For the three-ship formation, results were inconclusive due to the difficulty in properly maintaining the position of all aircraft simultaneously. Pilot workload assessments were also completed. Maintaining the minimum drag formation was considered to be of comparable workload to maintaining other types of formations. Of the four lateral positions tested, the one that was considered the easiest to fly was also the one that yielded the greatest fuel savings. The longest duration that the position could be maintained operationally was considered to be 20-30 minutes. This indicates that some sort of automatic system would probably be required to reap the benefits of formation flight for extended periods.

The technologies developed under these efforts are directly applicable to aerial refueling. One area of current interest is autonomous refueling of a UAV. Sophisticated control systems, position sensors, and a complete understanding of the effects of the wake of the tanker on the UAV will be required to attain this capability. The Langley facility is already being used to study wake interference effects during aerial refueling.

This article was written by Mr William Blake of the Air Force Research Laboratory's **Air Vehicles Directorate.**

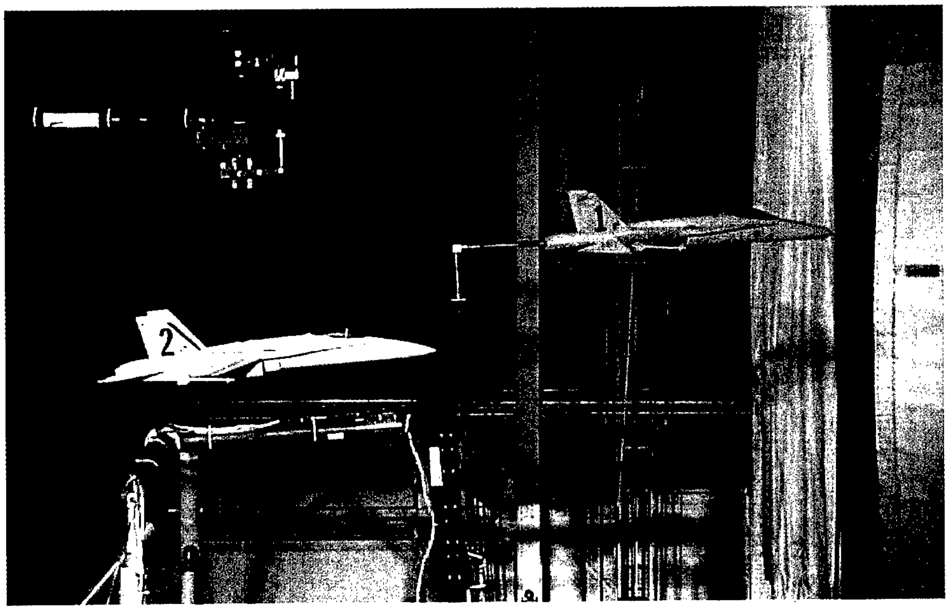

FIGURE 1. F-18C models in 30x60ft wind tunnel

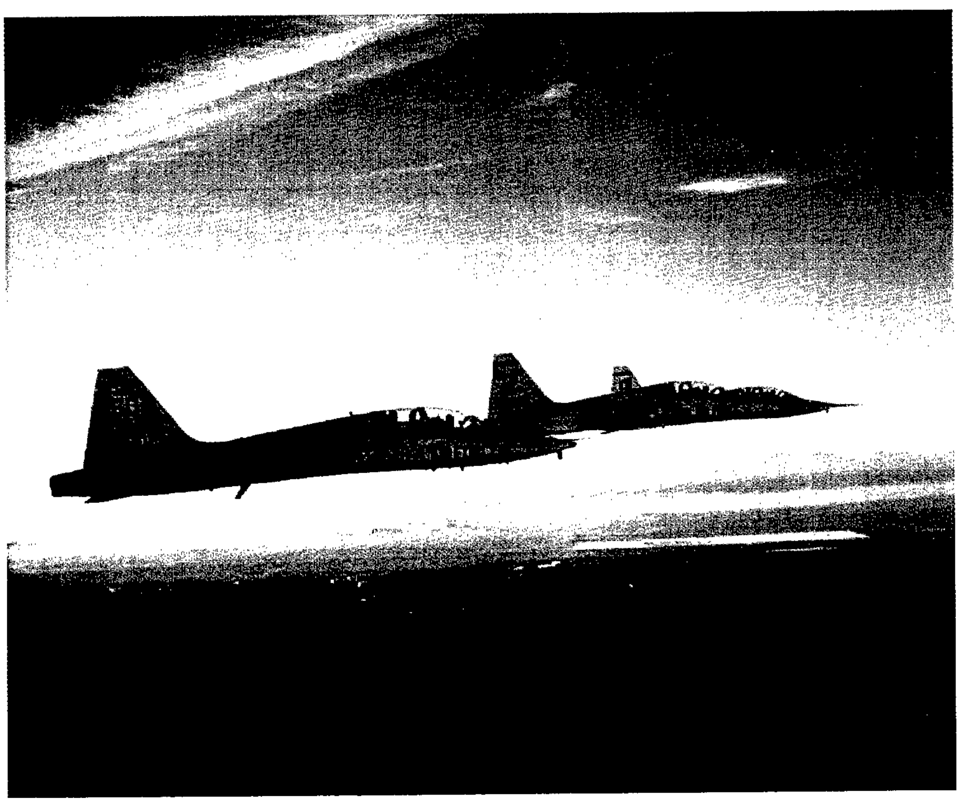

FIGURE 2. T-38 Formation flight